

Probing Higgs-boson Yukawa couplings at hadron colliders

Laura Reina

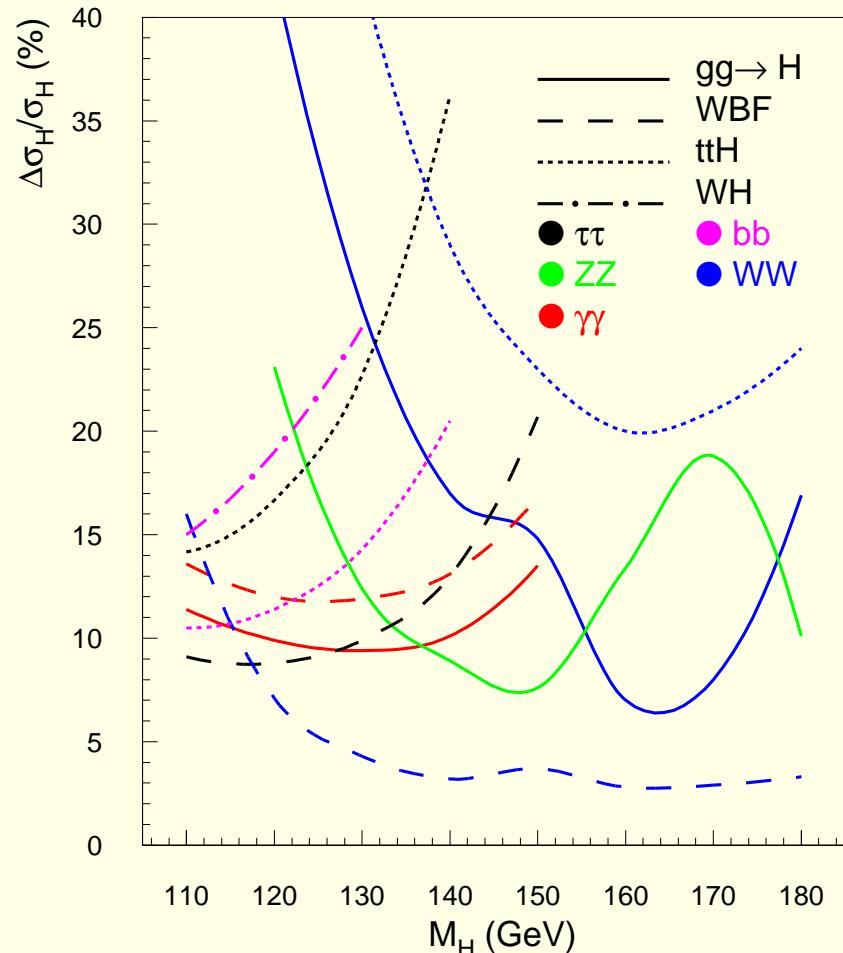
Brookhaven Forum, May 2007

Higgs-boson couplings to bottom and top quarks
via $b\bar{b}H$ and $t\bar{t}H$ production

- Overview, experimental reach, Tevatron vs LHC.
- Theoretical update: existing results, recent developments.

$pp \rightarrow t\bar{t}H$: unique direct measurement of top-quark Yukawa coupling

Probably not a discovery mode, but crucial in the Higgs coupling game.



← mostly 200 fb^{-1}

- Below 130-140 GeV

$gg \rightarrow H, H \rightarrow \gamma\gamma, WW, ZZ$

$qq \rightarrow qqH, H \rightarrow \gamma\gamma, WW, ZZ, \tau\tau$

$q\bar{q}, gg \rightarrow t\bar{t}H, H \rightarrow b\bar{b}, \tau\tau$

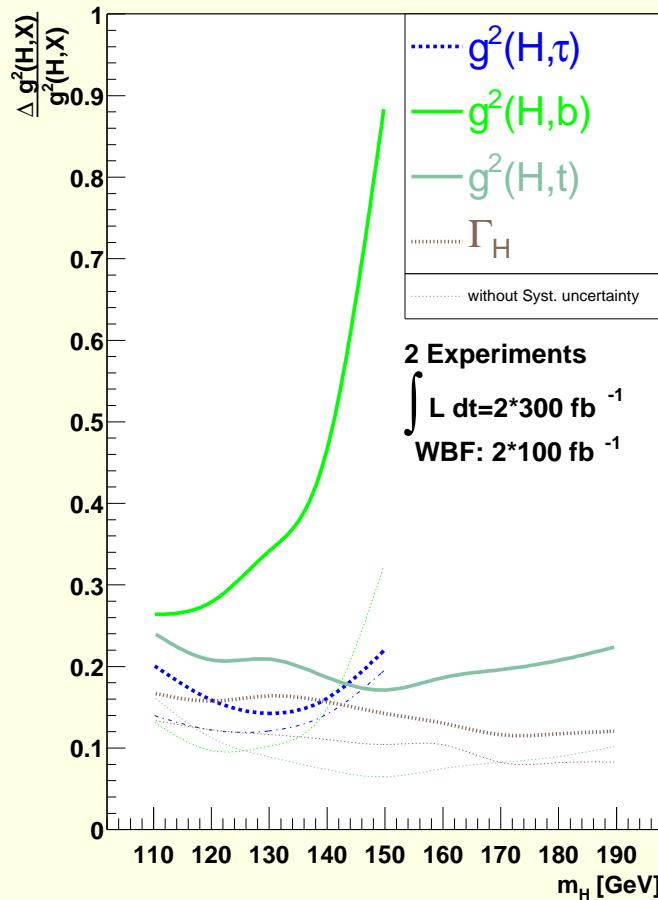
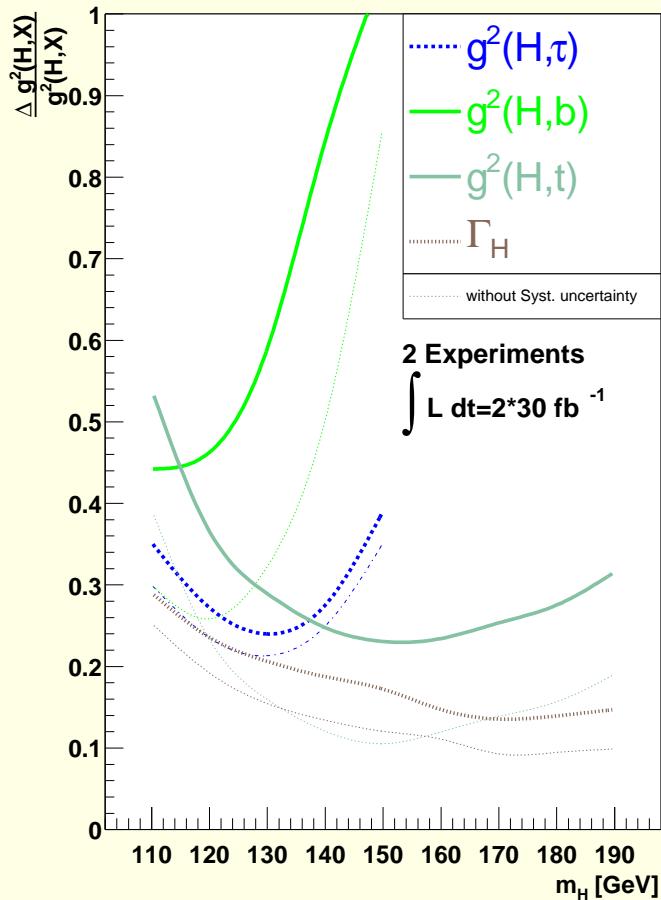
- Above 130-140 GeV

$gg \rightarrow H, H \rightarrow WW, ZZ$

$qq \rightarrow qqH, H \rightarrow \gamma\gamma, WW, ZZ$

$q\bar{q}, gg \rightarrow t\bar{t}H, H \rightarrow WW$

$t\bar{t}H$: F.Maltoni, D.Rainwater, S.Willenbrock, A.Belyaev, L.R.



Global χ^2 fit
assuming $\left\{ \begin{array}{l} \rightarrow g^2(H,V) < g^2(H,V,SM) \pm 5\% \quad (V = W, Z) \\ \rightarrow g^2(H,W)/g^2(H,Z) = g^2(H,W,SM)/g^2(H,Z,SM) \pm 1\% \\ \rightarrow \text{no new particles in loop production/decay modes} \end{array} \right.$

M.Dührssen, S.Heinemeyer, H.Logan,D.Rainwater, G.Weiglein, D.Zeppenfeld,

PRD 70:113009 (2004)

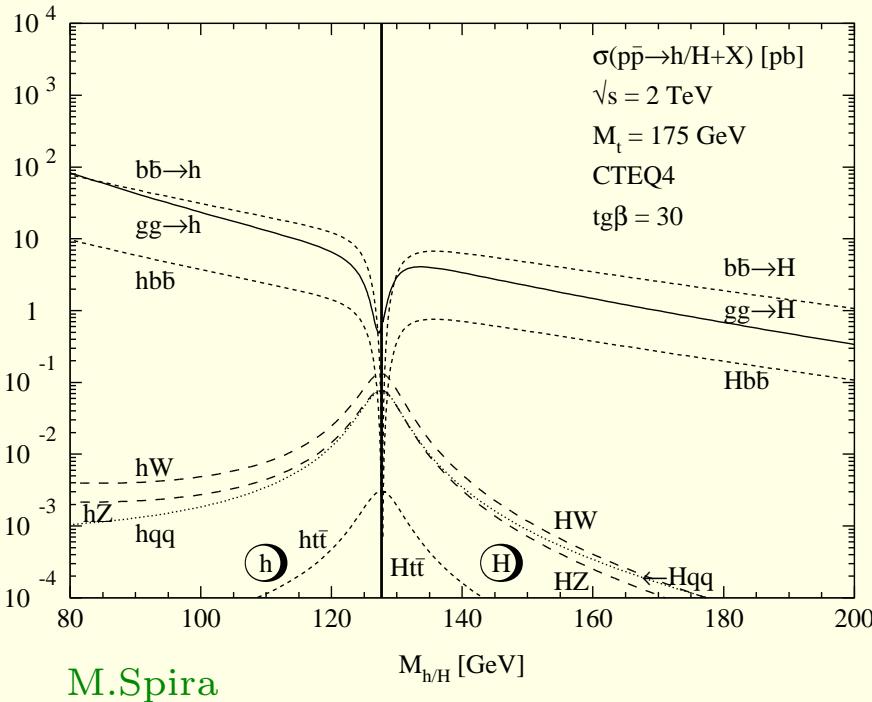
$p\bar{p}, pp \rightarrow b\bar{b}H$ important as a signal of new physics

Example: in the MSSM the bottom-quark Yukawa coupling can be enhanced with respect to the Standard Model:

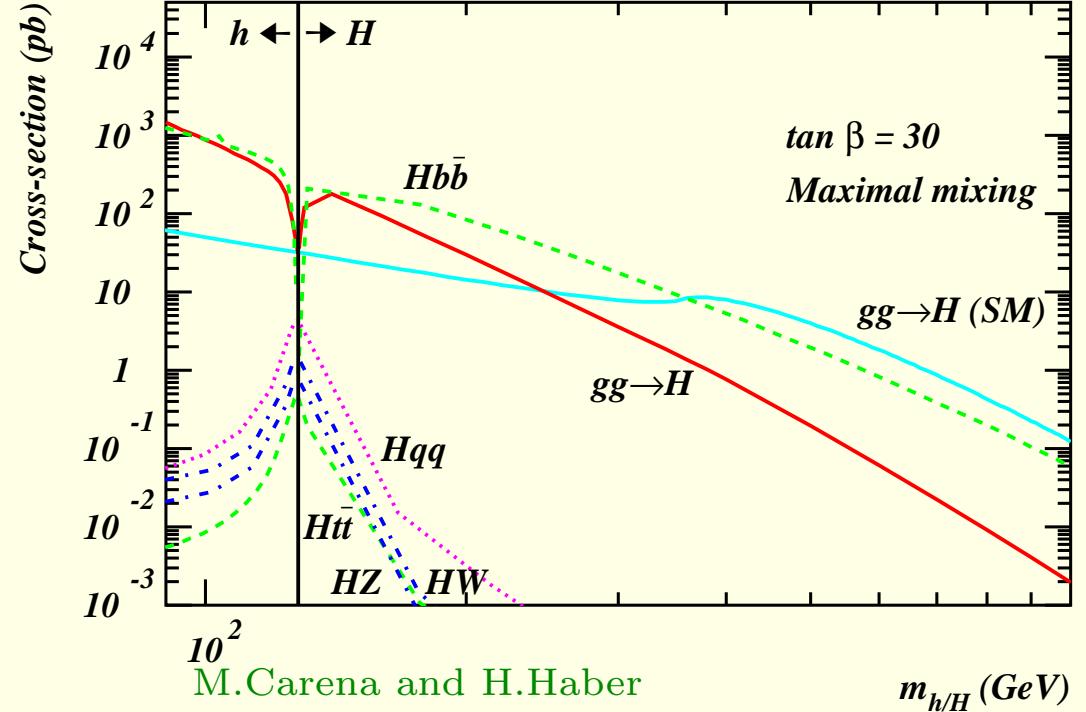
$$g_{b\bar{b}h^0, H^0}^{MSSM} = \frac{(-\sin \alpha, \cos \alpha)}{\cos \beta} g_{b\bar{b}H} \quad \text{and} \quad g_{b\bar{b}A^0}^{MSSM} = \tan \beta \ g_{b\bar{b}H}$$

where $g_{b\bar{b}H} = m_b/v \simeq 0.02$ (Standard Model) and $\tan \beta = v_1/v_2$ (MSSM).

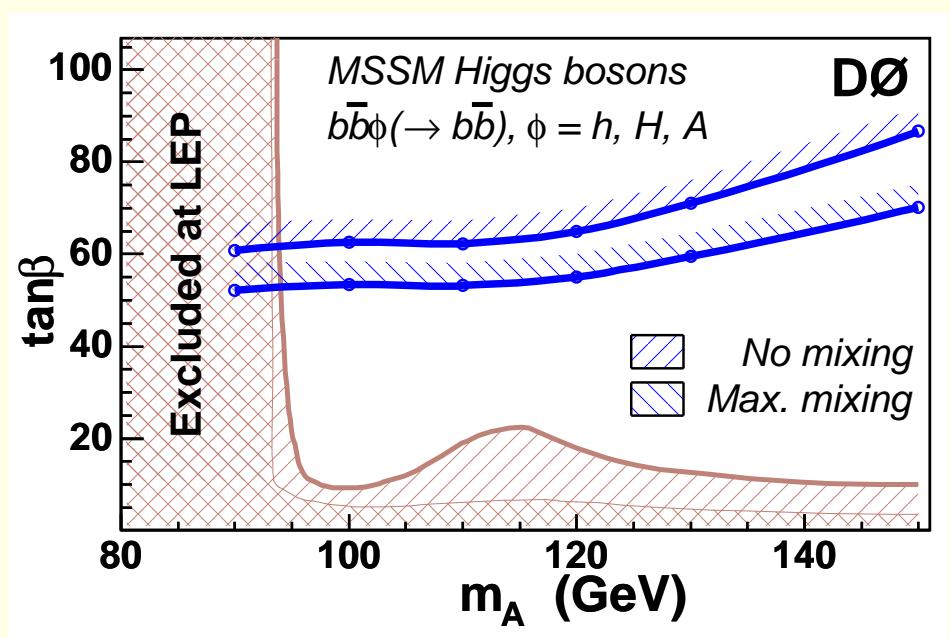
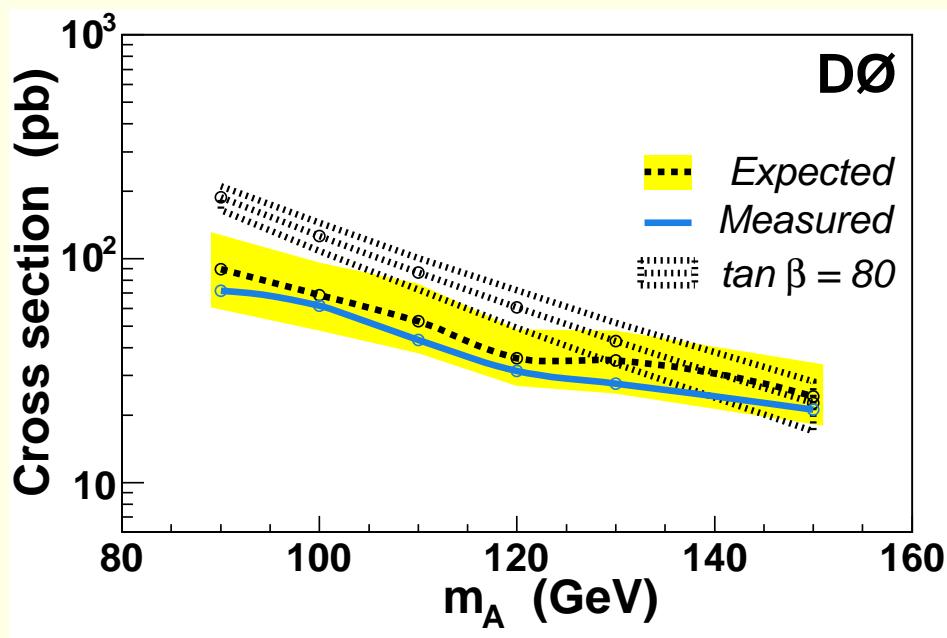
Tevatron



LHC



Tevatron searches: D \emptyset Run II data with 3 b -tagged events
(PRL 95 (2005) 151801)



Significant region of the MSSM parameter space can be excluded

Towards precise theoretical predictions

$\sigma(p\bar{p}, pp \rightarrow t\bar{t}H)$ calculated at $\mathcal{O}(\alpha_s^3)$:

- W.Beenakker, S.Dittmaier, M.Krämer, B.Plümper, M.Spira, P.M.Zerwas (PRL 87(2001), NPB 653(2003))
- S.Dawson, L.R., D.Wackerlo (PRL 87(2001), PRD 65(2002))
- S.Dawson, C.Jackson, L.H.Orr, L.R., D.Wackerlo (PRD 67(2003), PRD 68(2003))

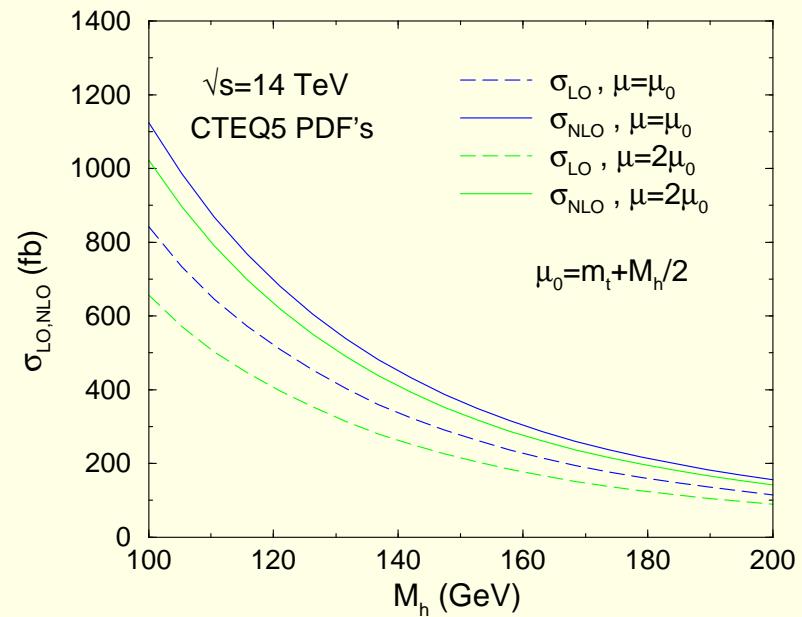
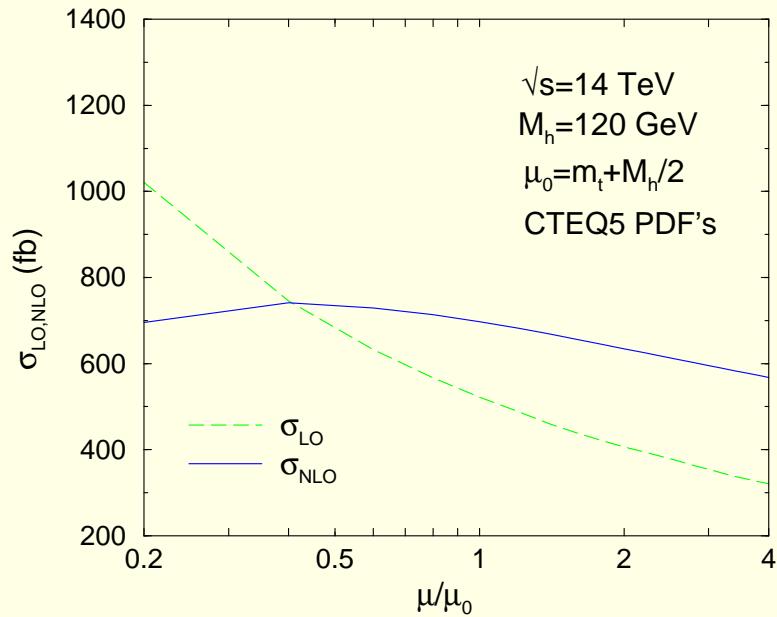
$\sigma(gg, q\bar{q} \rightarrow b\bar{b}H)$ calculated at $\mathcal{O}(\alpha_s^3)$:

- S.Dittmaier, M.Krämer, M.Spira (PRD 70 (2004))
- S.Dawson, C.Jackson, L.R., D.Wackerlo (PRD 69 (2004), PRL 94 (2005), MPL A21 (2006))

$\sigma(bg \rightarrow bH, b\bar{b} \rightarrow H)$ calculated at NLO (NNLO) in the 5FNS:

- J.Campbell, R.K.Ellis, F.Maltoni, S.Willenbrock (PRD 67 (2003))
- D.Dicus, S.Stelzer, Z.Sullivan, S.Willenbrock (PRD 59 (1999))
- R.Harlander, W.Kilgore (PRD 68 (2003))
- J.Campbell et al. (hep-ph/0405302, Les Houches 2003 Higgs Working Group)
- B.Field, C.B.Jackson, L.R. (arXiv:0075:0035, April 2007)

LHC, $pp \rightarrow t\bar{t}H$: NLO cross section



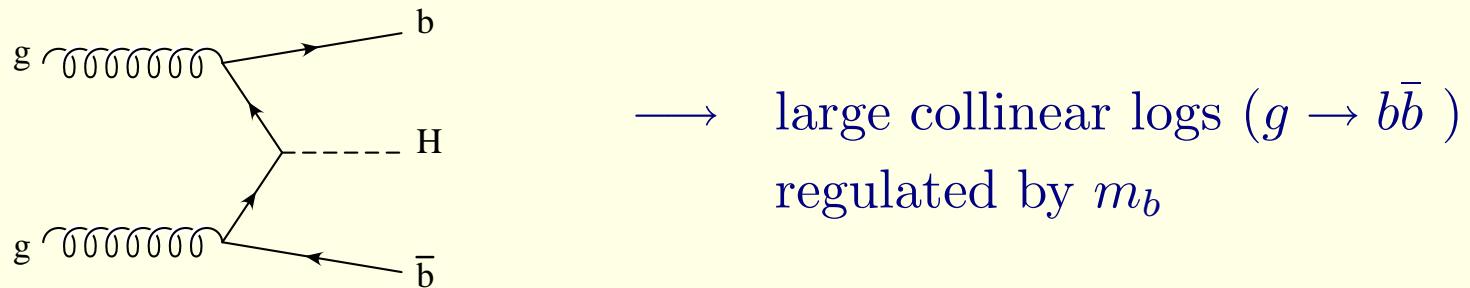
Theoretical uncertainty reduced to about 15%

S.Dawson, C.Jackson, L.H.Orr, L.R., D.Wackerlo

$$K = \frac{\sigma_{NLO}}{\sigma_{LO}} > 1 \quad \text{for most values of } \mu \text{ and } M_H$$

$p\bar{p}, pp \rightarrow b\bar{b}H$: exclusive vs inclusive cross section

- b-quarks identification requires tagging (p_T^b and η^b cuts): exclusive (1 b-, 2 b-tags) vs inclusive (1 b-, 0 b-tags) cross section.
- Exclusive modes have smaller cross section, but also smaller background and they measure the bottom-quark Yukawa coupling unambiguously.
- Inclusive modes enhanced by large collinear $\ln(\mu_H^2/m_b^2)$ arising in the PS integration of untagged b -quarks in $gg \rightarrow b\bar{b}H$



They can be resummed by introducing a b -quark PDF:

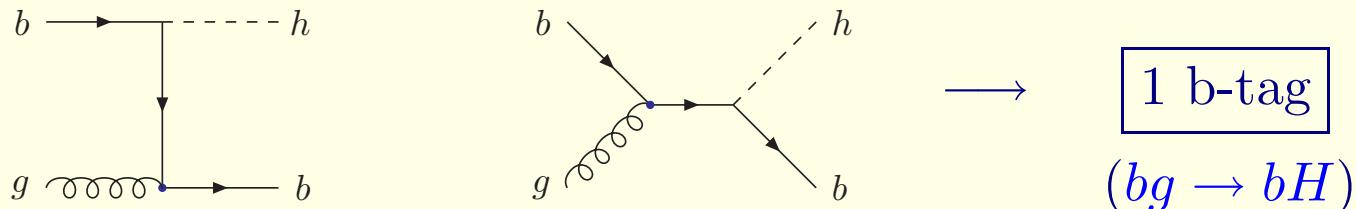
$$b(x, \mu) = \frac{\alpha_s(\mu)}{2\pi} \log \left(\frac{\mu^2}{m_b^2} \right) \int_x^1 \frac{dy}{y} P_{qg} \left(\frac{x}{y} \right) g(y, \mu)$$

- Semi-(ex/in)clusive and inclusive cross sections: 2 approaches

→ Use $q\bar{q}, gg \rightarrow b\bar{b}h$ (at NLO) → 4FNS

imposing tagging cuts on only one or no final state b quarks.

→ Use b -quark PDF, resumming the large collinear logs → 5FNS



Perturbative series ordered in Leading and SubLeading powers of $\alpha_s \ln(\mu_H^2/m_b^2)$. Need to consider (avoiding double counting)

▷ $b\bar{b} \rightarrow H$ (known at NNLO) → $\alpha_s^2 \ln^2(\mu_H^2/m_b^2)$

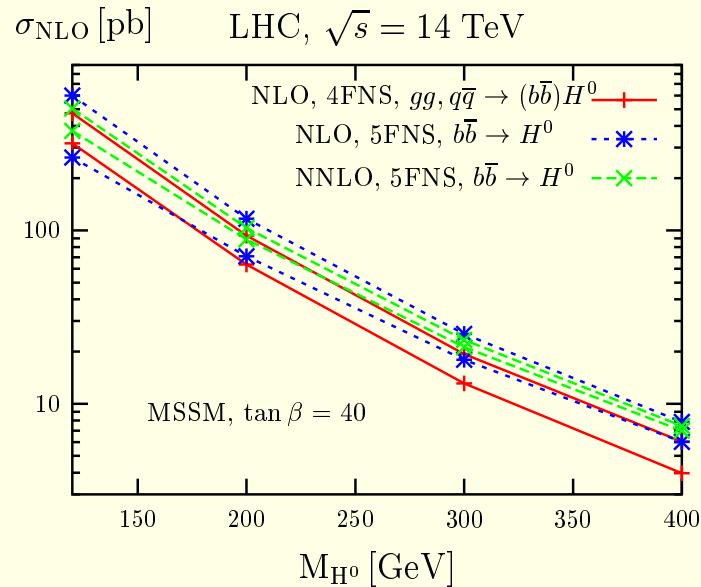
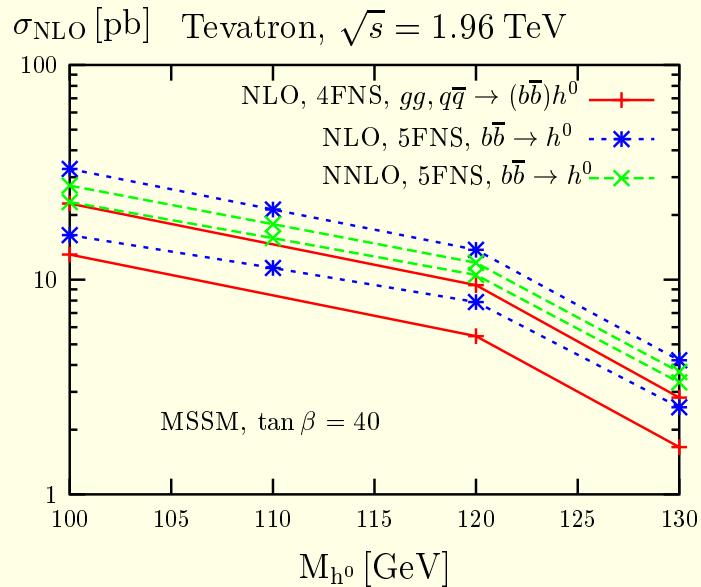
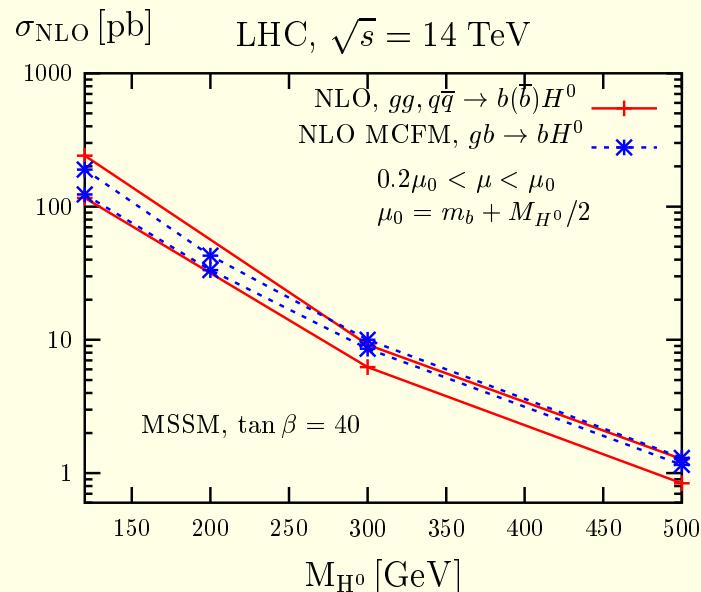
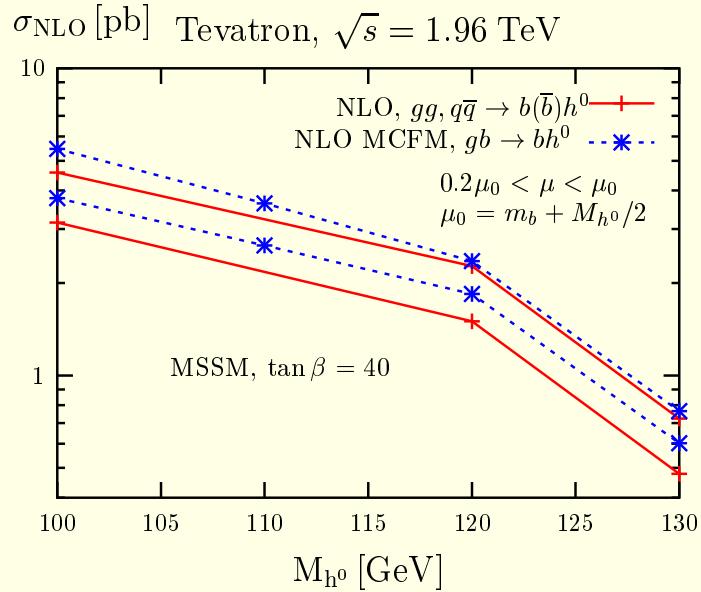
(R.Harlander, W.Kilgore; D.Dicus, T.Stelzer, Z.Sullivan, S.Willenbrock)

▷ $bg \rightarrow bH$ (known at NLO) → $\alpha_s^2 \ln(\mu_H^2/m_b^2)$

(J.Campbell, R.K.Ellis, F.Maltoni, S.Willenbrock)

▷ $gg \rightarrow b\bar{b}H$ (need LO only) → α_s^2

Inclusive cross sections in the MSSM: 4FNS vs 5FNS



Inclusive cross section with resummation of soft corrections

B.Field, C.B.Jackson, L.R. (arXiv:0075:0035, April 2007)

Consider resummation of soft corrections to $bg \rightarrow bH$: higher-order corrections expressed in terms of the leading-order cross section times color structure dependent coefficients (c_1, c_2, c_3).

At NLO-NLL:

$$\hat{\sigma}^{(1)} = \hat{\sigma}^{(0)} \frac{\alpha_s}{\pi} \{c_3 \mathcal{D}_1(\hat{s}_2) + c_2 \mathcal{D}_0(\hat{s}_2) + c_1 \delta(\hat{s}_2)\} ,$$

where

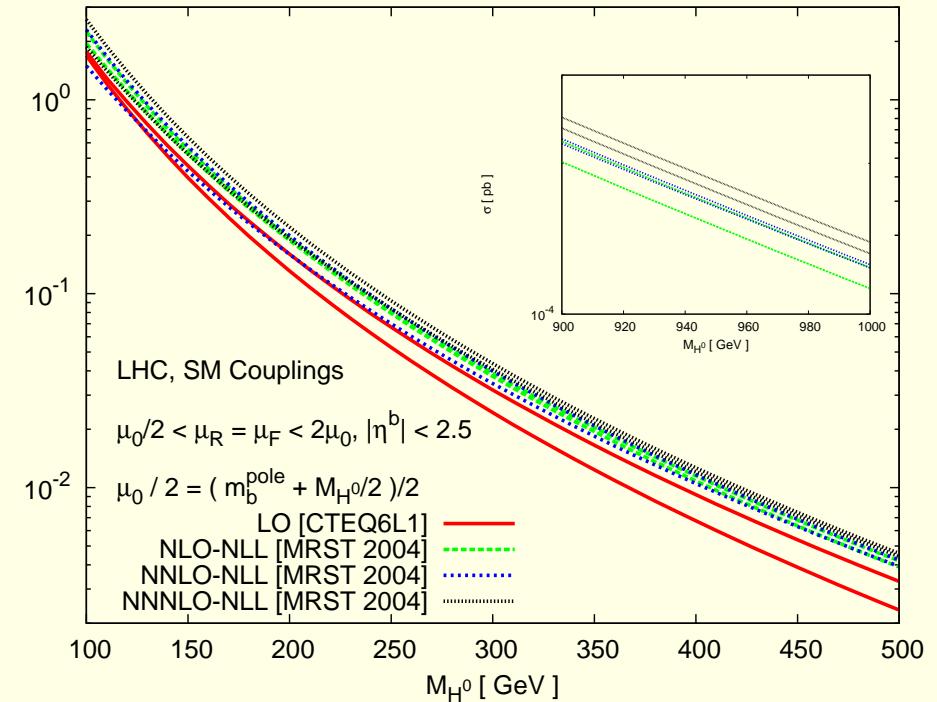
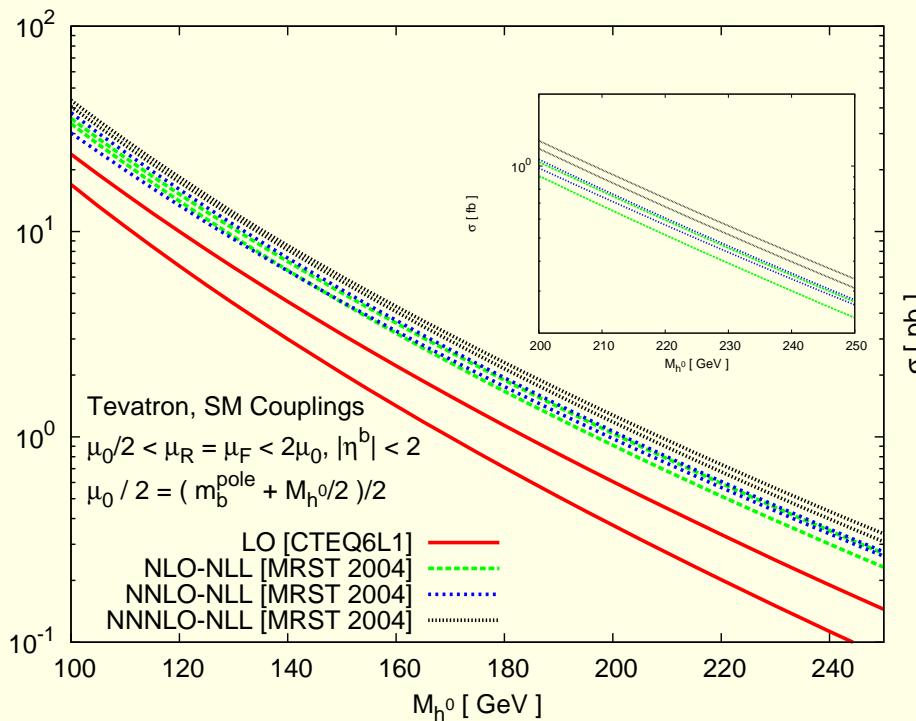
$$\mathcal{D}_l(\hat{s}_2) \equiv \left[\frac{\ln^l(\hat{s}_2/M^2)}{\hat{s}_2} \right]_+, \quad \hat{s}_2 = \hat{s} + \hat{t} + \hat{u} - \sum_i m_i^2$$

NNLO-NLL and NNNLO-NLL results also available:

$$\hat{\sigma}^{(2)} = \hat{\sigma}^{(0)} \left(\frac{\alpha_s}{\pi} \right)^2 F(c_1, c_2, c_3, \mathcal{D}_0, \dots, \mathcal{D}_3)$$

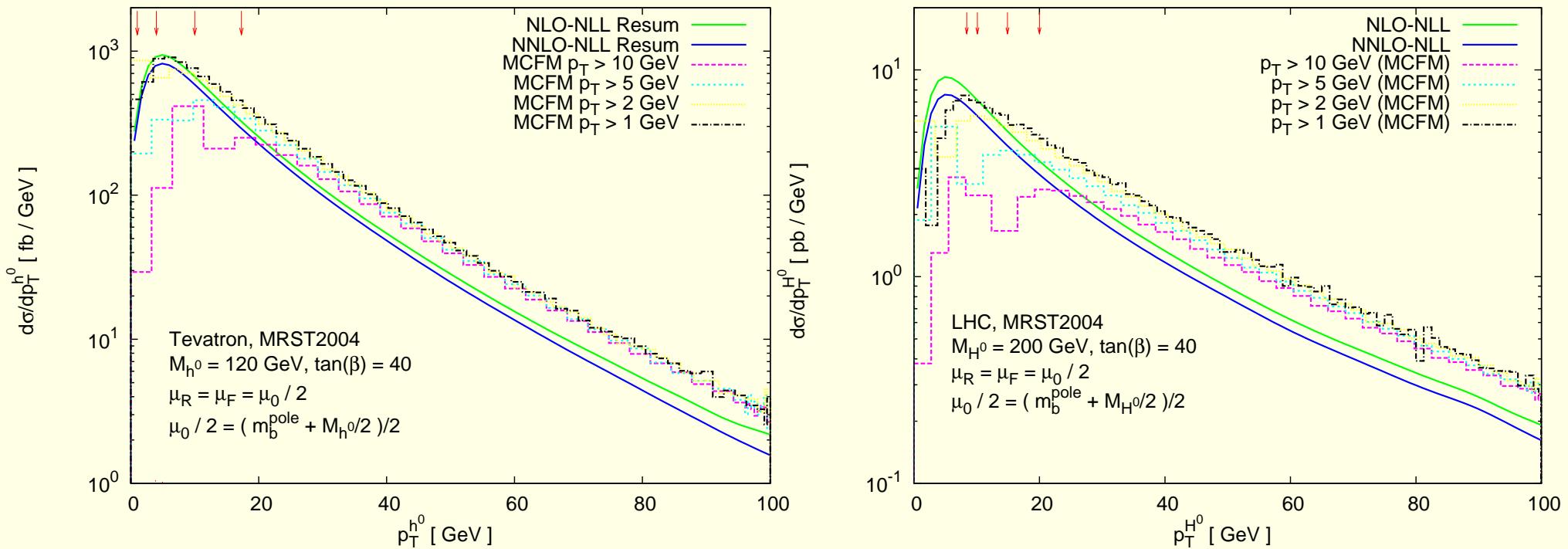
$$\hat{\sigma}^{(3)} = \hat{\sigma}^{(0)} \left(\frac{\alpha_s}{\pi} \right)^3 F(c_1, c_2, c_3, \mathcal{D}_1, \dots, \mathcal{D}_5)$$

Stability of resummed perturbative expansion:



- ▷ NLO-NLL, NNLO-NLL: fully consistent parameters (α_s , m_b) and PDF's.
- ▷ NNNLO-NLL: mismatch at the PDF level.

Improved distributions at low p_T^Φ :



- ▷ NLO fixed order and NLO-NLL results in good agreement up to $\simeq \mu_R = \mu_F$;
- ▷ NLO-NLL smoothly interpolates the low p_T^ϕ region;
- ▷ higher order resummed cross sections improve predictions where most of the statistics is accumulated;
- ▷ caution: $2 \rightarrow 2$ kinematics, prediction reliable above the p_T^b cut.

Conclusions

- $t\bar{t}H$, $b\bar{b}H$ instrumental to the measurement of top- and bottom-quark Yukawa couplings at hadron colliders (Tevatron, LHC).
- Crucial to have calculated NLO QCD corrections:
 - ▷ $t\bar{t}H$ and $b\bar{b}H$: theoretical uncertainty greatly reduced;
 - ▷ $b\bar{b}H$: comparison between 4FNS and 5FNS now under control.
- Recent improvement: resummed soft corrections to NNNLO-NLL for $bg \rightarrow bH$:
 - ▷ added stability to low region of the p_T^Φ distribution.